Acoustics in Uncertain Ocean Environments

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LONG-TERM GOALS

The long term goals of this project are:

1) to quantitatively predict the uncertainties in underwater sound propagation predictions that arise from uncertainty in environmental parameters,

2) to determine how to exploit in-situ acoustic measurements and the generic propagation characteristics of underwater sound channels in order to enhance the performance of active and passive sonar systems in unknown or uncertain ocean environments, and

3) to predict and understand the characteristics of active and passive time reversal methods in shallow ocean waters. Compared to the first two, the third goal is a secondary priority that stems from the legacy of more than a decade of prior work on acoustic time reversal. It is mentioned here because the author of this report does respond to the continuing technical inquiries and collaboration opportunities in this area when potential US Navy interests are apparent and when such commitments do not adversely impact progress toward the first two goals.

OBJECTIVES

This project seeks to quantitatively determine what can be accomplished with underwater sound in uncertain ocean environments. The capabilities of future Navy sonar systems will be enhanced if they can fully exploit modern calculation techniques for underwater sound propagation. Unfortunately, the US Navy must commonly operate in imperfectly known ocean waters so sound propagation calculations are inherently uncertain because of the lack of knowledge of environmental parameters and boundary conditions. However, the accuracy limits of sound propagation calculations with uncertain input parameters and boundary conditions are not readily determined from the calculation routines themselves. Thus, the present objectives of this project are: a) to quantitatively predict the uncertainty in ocean acoustic propagation calculations that comes from uncertainty in the parameters used to specify the computer-model environment for the acoustic propagation calculations, and b) to determine how to utilize propagation modeling and in-situ acoustic measurements to develop accurate acoustic field predictions for complex reverberant environments.

Report Documentation Page	*Form Approved* *OMB No. 0704-0188*

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1. REPORT DATE **30 SEP 2005**	2. REPORT TYPE	3. DATES COVERED **00-00-2005 to 00-00-2005**
4. TITLE AND SUBTITLE **Acoustics in Uncertain Ocean Environments**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of Michigan,Department of Mechanical Engineering,Ann Arbor,MI,48109**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
code 1 only

14. ABSTRACT
The long term goals of this project are 1) to quantitatively predict the uncertainties in underwater sound propagation predictions that arise from uncertainty in environmental parameters 2) to determine how to exploit in-situ acoustic measurements and the generic propagation characteristics of underwater sound channels in order to enhance the performance of active and passive sonar systems in unknown or uncertain ocean environments, and 3) to predict and understand the characteristics of active and passive time reversal methods in shallow ocean waters. Compared to the first two, the third goal is a secondary priority that stems from the legacy of more than a decade of prior work on acoustic time reversal. It is mentioned here because the author of this report does respond to the continuing technical inquiries and collaboration opportunities in this area when potential US Navy interests are apparent and when such commitments do not adversely impact progress toward the first two goals.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**7**	

APPROACH

This project primarily exploits analytic and computational propagation models for narrowband and broadband sounds in simple and complicated acoustic environments. The work also includes a related experimental effort, with joint support from ONR Code 333, that involves laboratory-scale sound source localization in reverberant environments. In particular, analytical propagation models are used for free-space (single path) and stratified two-fluid (two path) environments. Sound propagation in an ocean sound channel is simulated with the range-depth (2D) wide-angle parabolic-equation code RAM (by Dr. Michael Collins of NRL) and the mode-based propagation code KRAKEN (by Dr. Michael Porter). The experimental work currently emphasizes detection and localization of hydrodynamic cavitation sound sources and is conducted in the test section of a water tunnel with a 16-hydrophone array having ~200 kHz bandwidth. My current graduate students, Ms. Natasha Chang and Mr. Kevin James, are pursuing experimental and theoretical efforts, respectively, related to complex and uncertain environments.

WORK COMPLETED

During the past year, this project has had two main thrusts:

i)   determining how the joint probability density function for the real and imaginary parts of a harmonic sound field evolves in an uncertain environment for increasing source-receiver range and increasing frequency, and

ii)   utilizing the hydroacoustic source localization system developed last year to localize a controlled sound source emitting a broadband pulse in a water tunnel test section.

The first thrust on quantifying the relationship between environmental uncertainty and predicted-acoustic-field uncertainty has proceeded far enough so that Mr. Kevin James and the author of this report are now truly grappling with the difficulties of this task. Two potentially viable theoretical approaches to this problem have been identified:

i)   solution of probability transport equations, and

ii)   transformation of parameter probability distributions into field probability distributions. Theoretical development of the first approach and results involving sound propagation in one and two spatial dimension have been completed, written up, and submitted and accepted for publication [1].

The second effort has primarily involved development of data-acquisition software, array-mounting hardware, and signal processing routines. Preliminary localization results have been obtained from a controlled sound source in a fish tank using both ray-based and mode-based signal processing schemes. Analyses of recent measurements in a laboratory-scale water tunnel at the University of Michigan are currently underway. All the instrumentation and hardware costs were covered by ONR funding from Dr. Ki-Han Kim, ONR Code 333. The present ONR project has shared the salary and tuition costs for Ms. Natasha Chang in the last fiscal year.

RESULTS

The first results from the effort to link environmental uncertainties and acoustic field uncertainties were obtained by solving the probability-density-function transport equations for uncertain harmonic plane waves. If R and I are the real and imaginary parts of the acoustic field from a plane wave source of uncertain amplitude at frequency ω inside a pipe having an uncertain wave number, the joint probability density function, f_P for R and I as a function of source-receiver distance x is:

$$f_P(R,I;x) = \frac{f_A\left(\sqrt{R^2 + I^2}\right)}{x\sqrt{R^2 + I^2}} \sum_n f_K\left(\frac{\tan^{-1}(I/R) - 2\pi n}{x}\right) \quad \text{for} \quad I > 0 ,$$

where f_A is the amplitude distribution of the source, and f_K is the wave number distribution inside the pipe. Here, $2\pi n$ in the argument of f_K should be replaced by $2\pi(n-1/2)$ when $I < 0$, and the sum over the index n extends over all values of the summand that are non-zero. When this f_P is plotted, this equation quantifies how, even in this geometrically-simple case, increasing source-receiver range and increasing frequency lead to increased sound field uncertainty.

The extension of these one-dimensional results to the usual two spatial dimensions (range and depth) of underwater sound calculations has been challenging because, unlike the one-dimensional case, simple closed form algebraic relationships for the acoustic field do not exist in two dimensions. This situation has lead to consideration of probability density transformation techniques as a more general means of obtaining f_P from the distributions of the uncertain parameters. So far this technique appears computationally tractable for one, two, or possibly three uncertain parameters. A sample calculation of f_P is shown on Figure 1 in isometric (a) and overhead (b) views for a nominal source-receiver range of 20 km at 500 Hz in an ideal isospeed sound channel with an uncertain depth of 100m $\pm$ 1m. The main point of interest here is that the spread in likely field amplitudes exceeds 20 dB and all phases are equally likely. Thus, the value of any single propagation prediction made under these circumstances is suspect.

At the present time, probability density transformation techniques and the waveguide invariant are being used in combination to assess the impact of uncertainties in signal frequency and sound speed in computational ocean waveguides.

The main idea for the second effort is to use underwater sound source localization techniques, such as matched field processing (MFP), to locate hydroacoustic sound sources during hydrodynamic testing of propulsors, hull forms, control surfaces, etc. The main technical challenge is to develop an environmental modeling strategy with the flexibility to incorporate propagation data measured in a water tunnel, towing basin, or other hydrodynamic testing facility. The current localization system is based on 16 hydrophones having a nominal bandwidth of 200 kHz, and it is deployed in a laboratory-scale water tunnel at the University of Michigan having a 8-inch by 8-inch test-section cross section. The system is portable enough for use at US Navy test facilities in (and near) Washington DC, and at the William B. Morgan Large Cavitation Channel in Memphis, TN (3.05 m by 3.05 m test section cross section).

The second research effort on hydroacoustic source localization has made significant progress in three-dimensional localization of a controlled sound source in a fish tank and in the water tunnel test section.

Both straight-ray time-of-flight and low-order-mode matched-field processing (MFP) schemes have been used. A sample of the output from the MFP work using four hydrophones is shown in Figure 2. The signal-processor-determined source location (brown spot) and actual source location (the "O") are coincident. However, these results are based on incoherent Bartlett MFP for 12 signal frequencies between 4.75 kHz and 15.75 kHz, less than 10% of the available signal bandwidth. Thus, the current emphasis of this effort is the development a robust high-frequency ray-based localization technique that compensates for hydrophone location errors and complements these MFP results.

IMPACT/APPLICATION

In broad terms, this project seeks to determine what is possible for a sonar system when the available environmental and transducer-array information is less than perfect. The capabilities of future Naval sonar systems will be enhanced if acoustic propagation predictions and their uncertainty can be properly included in final results or in a tactical decision aid. Thus, the research effort on quantifying predicted-field uncertainties should eventually impact how transducer (array) measurements are processed for detection, localization, and identification. Moreover, this research should eventually provide a means for assessing acoustic uncertainties that is not available today. The current and on-going work on hydroacoustic source localization addresses:

i) the operational need to combine propagation modeling and in-situ experimental measurements to develop a working field model for complex reverberant environments, and

ii) the testing and development need for a robust sound source localization capability for hydrodynamic testing environments.
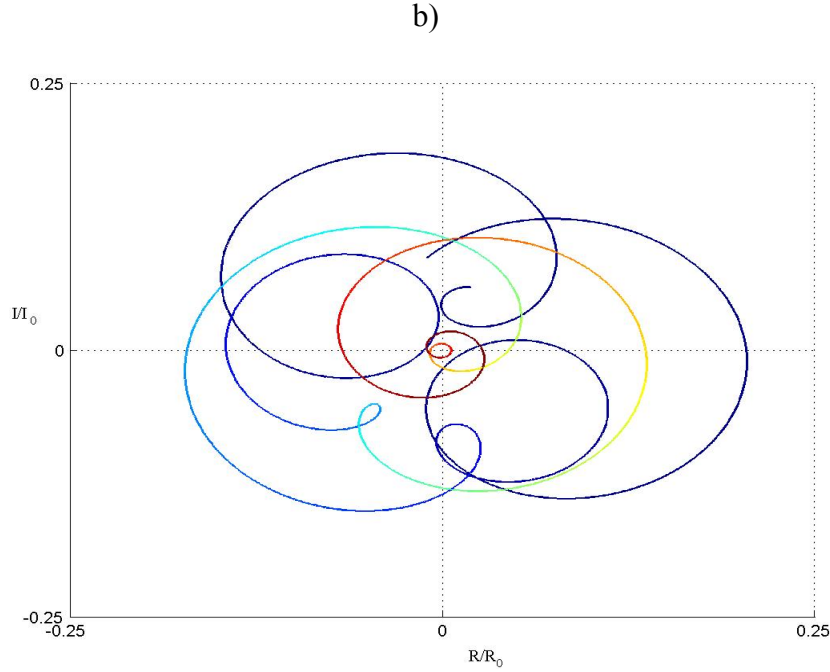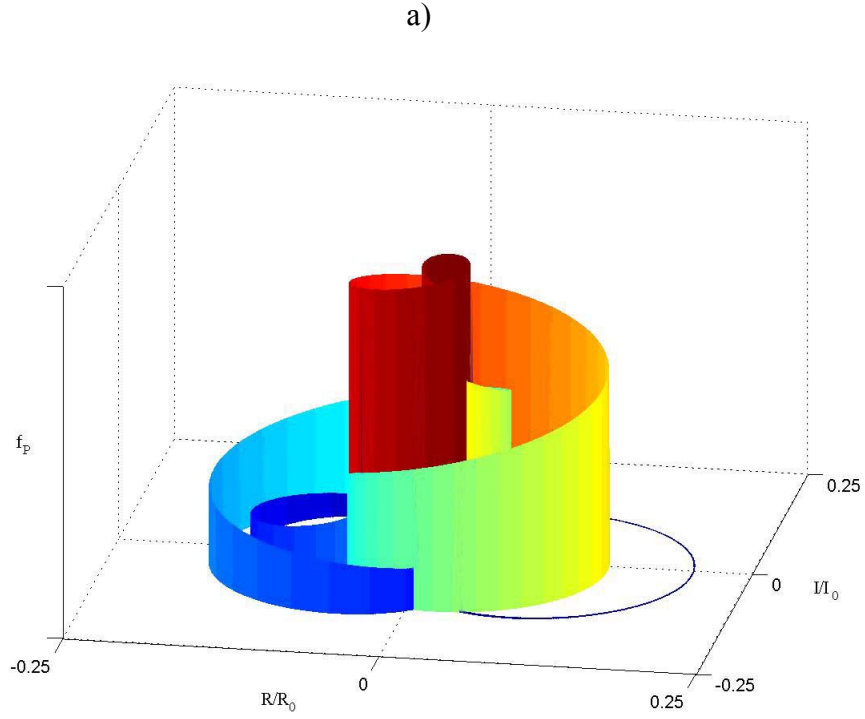
a)

b)

Figure 1. Isometric (a), and overhead (b) views of the joint probability density function for the real, R, and imaginary, I, parts of a 500 Hz harmonic field in an ideal sound channel with an uncertain depth. Here, R and I have been range normalized to account for cylindrical spreading, the expected value of the channel depth is 100 m, and the standard deviation of the channel depth is 1m. The source and the receiver depths are both 50m and the source-receiver range is 20 km. Under these conditions, the uncertainty in the predicted acoustic field is likely to render the predictions useless.
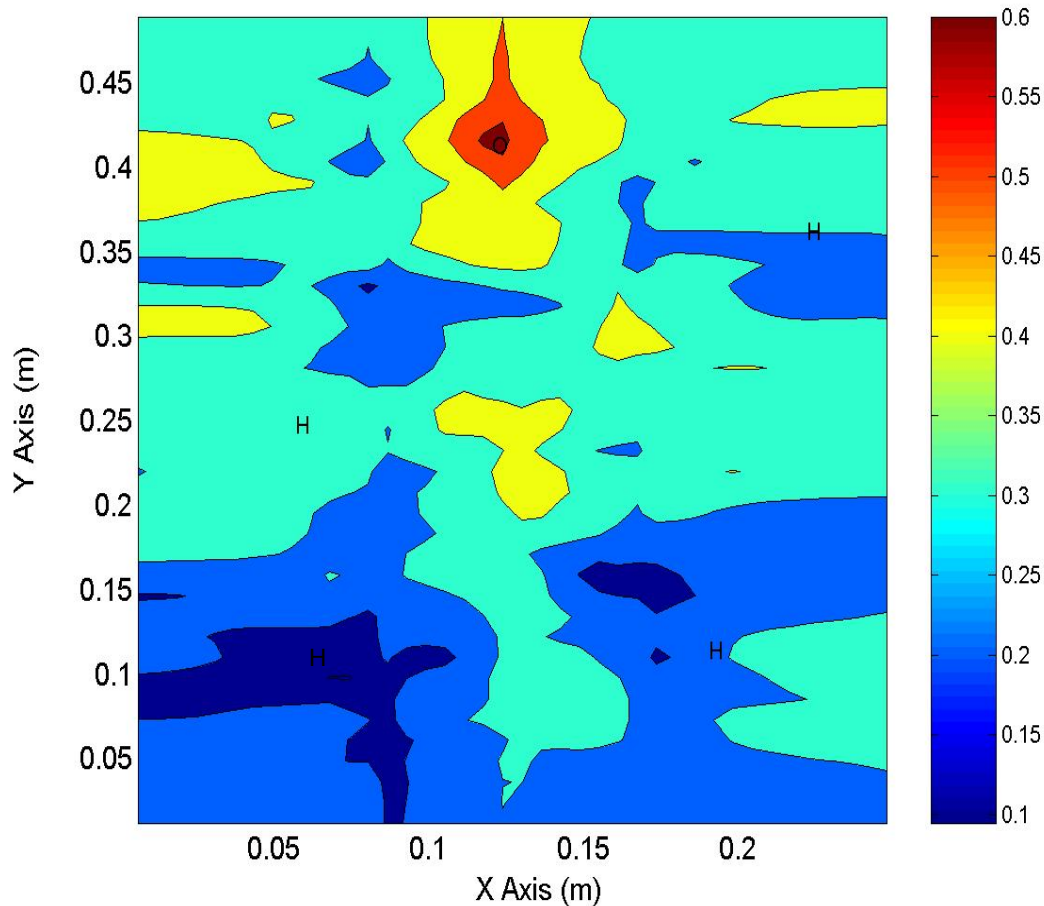
Figure 2. Broadband matched field processing output in the plane of a controlled acoustic source located at "0" in a fish tank using four hydrophones. The projected locations of the four hydrophones on this plane are marked by the letter "H". Signal frequencies between 4.75kHz and 15.75 kHz were incoherently combined to generate this result. Although this localization result is good, it merely utilizes less than 10% of the available signal bandwidth.

TRANSITIONS

The results of this project should aid in the design of sonar signal processors and in determining which features of an acoustic environment must be known accurately for effective sonar operations. In addition, ONR's hydroacoustics group in Code 333 and researchers at the Naval Surface Warfare Center - Carderock Division are interested in using modern underwater sound localization techniques to detect, localize, and classify subvisual cavitation events and other hydrodynamic sound sources.

RELATED PROJECTS

1. The now-fading time reversal portion of this research project runs parallel to the time-reversal experiments and analysis of the international research team headed by Drs. William Kuperman and William Hodgkiss of Scripps Institution of Oceanography (SIO). Data from their landmark experiments has been shared for use in the study of mode-based and ray-based blind deconvolution techniques based on time reversal. In addition, a new summary of underwater acoustic time reversal [2] has been co-authored by the author of this report and Dr. HeeChun Song from the SIO time-reversal team.

2. A verbal agreement is in place with Dr. George Smith of NRL-Stennis to coordinate and collaborate on future blind deconvolution efforts.

3. The work on hydroacoustic source localization in complex reverberant environments is jointly funded. Support for the graduate student involved in this effort is shared with the ONR-funded cavitation research project directed by Prof. Steven L. Ceccio of the University of Michigan.

4. Verbal agreements are in place with Dr. Steve Finette of NRL-DC and Dr. Lee Culver of the Penn-State ARL to coordinate and possibly collaborate on topics involving predicted-field uncertainties. Dr. Finette leads an NRL funded effort on acoustic uncertainty, and Dr. Culver is a co-investigator on an ONR-funded signal processing project on the impact of uncertainty on sonar signal processing.

REFERENCES AND PUBLICATIONS

[1] James, K.R., and Dowling, D.R. "A probability density function method for acoustic field uncertainty analysis," in press, J. Acoust. Soc. Am., August 2005.

[2] Dowling, D.R. and Song. H.C., in "Sounds in the Sea" edited and authored by H. Medwin, (Cambridge University Press, 2005), Ch. 19, pp. 481-499.

HONORS/AWARDS/PRIZES

David R. Dowling was promoted to full professor of Mechanical Engineering and Applied Mechanics at the University of Michigan effective September 1, 2005.